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Motorcycle active safety systems: Assessment of the function and applicability using a population-based crash dataset

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ABSTRACT

Objective: Motorcycles and mopeds, often referred to as powered two wheelers (PTWs), play an important role for personal mobility worldwide. Despite their advantages, including low cost, space and fuel efficiency, the risk of sustaining serious or fatal injuries is higher than is the case for occupants of passenger cars. The development of safety systems specific for PTWs represents a potential way to reduce casualties among riders. With the proliferation of new active and passive safety technologies, the question as to which might offer the most value is important. In this context, a prioritisation process was applied to a set of PTW active safety systems to evaluate their applicability to crash scenarios alone and in combination. The systems included in the study were antilock braking, autonomous emergency braking, collision warning, curve warning, and curve assist.

Methods: With the functional performance of the five safety systems established, the relevance of each system to specific crash configurations and vehicle movements defined by a standardized accident classification system used in Victoria, Australia, was rated by two independent reviewers, with a third reviewer acting as a moderator where disagreements occurred. Ratings ranged from 1 (definitely not applicable) to 4 (definitely applicable). Using population-based crash data, the number and percent of crashes that each safety system could potentially influence, or be relevant for, was defined. Applying accepted injury costs permitted the derivation of the societal economic cost of PTW crashes and the potential reductions associated with each safety system given a theoretical crash avoidance effectiveness of 100%.

Results: In the 12-year period 2000 - 2011, 23,955 PTW riders and 1292 pillion passengers were reported to have been involved in a road crash, with over 500 killed and more than 10,000 seriously injured; only 3.5% of riders / pillions were uninjured. The total economic cost associated with these injured riders and pillions was estimated to be \$AU 11.1 billion (US\$7.70 billion; €6.67 billion). The five safety systems, as single solution or in combination, were relevant to 57% of all crashes, and to 74% riders killed. Antilock braking was found to be relevant to the highest number of crashes, with incremental increases in coverage when combined with other safety systems.

Conclusions: The findings demonstrate that ABS, alone and in combination with other safety systems, has the potential to mitigate or possibly prevent a high percentage of PTW crashes in the considered setting. Other safety systems can influence different crash scenarios and are also recommended. Given the high cost of motorcycle crashes and the increasing number of PTW safety technologies, the proposed approach can be used to inform the process of selection of the most suitable interventions to improve PTW safety.

Keywords: Motorcycle, safety system, anti-lock braking (ABS), autonomous emergency braking (AEB), collision warning, curve warning, evaluation.

INTRODUCTION

Motorcycles and mopeds – often indicated as powered two-wheelers (PTWs) – can play a role as efficient personal powered mobility. Notwithstanding the advantages that PTWs may offer at personal and societal level, PTW use is characterised by high serious and fatal crash rates. In 2010 in Europe, moped and motorcycle fatalities were respectively 1094 and 4368, with a reduction in the period 2001-2010 being 51% and 17% respectively (EU-19, source CARE). Fatalities involving PTW users accounted for 18% of the deaths occurred in roads crashes (EU-24, source CARE 2010). Similarly in Victoria, Australia, in 2013 PTW fatalities represented 17% of all road casualties, despite accounting for only 3.4% of all registered fleet.

The introduction of effective safety technologies has led to dramatic improvements in passenger car safety (e.g. Lie *et al.* 2004, D'Elia *et al.* 2013). Given this, the development and deployment at large of specific safety systems for PTWs may represent in the future a key contribution to PTW safety.

Primary safety concepts were firstly applied to motorcycle brakes in the antilock braking systems more than two decades ago and these systems have been improved ever since. More recently, other safety systems for PTWs were introduced, such as a stability control for braking while cornering (De Filippi *et al.* 2014, Matschl 2014). In addition, solutions such as collision warning, autonomous emergency braking, and curve warning specifically for motorcycles have been described in the literature (Biral *et al.* 2010, Biral *et al.* 2012, Savino *et al.* 2012).

Given the list of safety systems available in the market or at prototype level, a prioritisation process is needed to identify those systems with the highest safety potential, i.e., those systems which are likely to influence the largest number of crashes. This can be termed 'device relevance.' This way, the resources for the regulatory process and for the development allowing for a wide penetration on the market can be concentrated on the most promising solutions.

In the present paper, we examined the likely device relevance of a set of five embedded active safety systems having the most promise according to a previous study (Gil *et al.* 2017), these being: antilock braking (ABS), autonomous emergency braking for motorcycles (MAEB), collision warning, curve warning, and curve assist.

We documented the relevance of the safety systems, alone and in combination, on the PTW crashes that occurred over the 12-year period 2000-2011 in Victoria, Australia, using a comprehensive national crash database. In doing so, the economic cost associated with PTW crashes was also estimated.

METHODS

Setting

The setting for the study was the State of Victoria, Australia. As at December 2011, Victoria had a population of 5.58 million persons (24.8% of Australian population), of which 49.5% were male ($n = 2,761,846$) and 50.5% were female ($n = 2,820,824$) (Australian Bureau of Statistics 2014). To hold a motorcycle learners permit, persons must be 18 years of age (VicRoads 2014a). As at August 2013, there were 236,076 holders of a PTW licence in Victoria (88% male), which represents approximately 6% of all licences held (VicRoads 2014b).

In 2011, there were 4,183,006 registered vehicles (i.e., 748 vehicles per 1000 persons), of which 78.9% ($n = 3.3$ million) were passenger vehicles, 13.4% were light commercial vehicles ($n = 559,427$) and 3.8% were trucks, buses and campervans ($n = 160,452$; 3.8%). In addition, there were 161,261 registered motorcycles accounting for 3.43% of the total registered fleet; 62.4% ($n = 100,549$) of these motorcycles were registered to owners residing in metropolitan (urban) Melbourne with the balance being registered in regional Victoria (Department of Transport 2012).

Data Sources

Data for the period 2000 - 2011 inclusive extracted from the Road Crash Information System (RCIS) were used in the analysis (details provided in the Appendix). Each crash is manually coded by VicRoads according to the Definition for classifying Accidents (DCA) chart using defined rules (Figure A1 in the Appendix). The DCA chart is divided into 10 categories (e.g., pedestrian, overtaking, off path on curve) with specific crash configurations described within. In total, there are 81 crash types, each one associated to a symbolic description for the trajectories of the vehicles involved in the crash; however, each vehicle is classified as vehicle 1, vehicle 2 etc. with the direction, intention and actual travel path determined. Using the DCA information, the 'relevance' of each of the selected safety systems was assessed.

Determination of the 'relevance' of selected safety system to motorcycle crashes

Using the DCA code and the vehicle movement coding scheme, the number of possible crash configurations expanded from 81 to 152. In fact, the expanded DCA code in multi-vehicle crash configurations univocally identified whether the motorcycle is vehicle 1, or vehicle 2, 3 etc. in each pictogram (see Figure A1 in the Appendix). Hence, the 'relevance' of each of the five safety systems being considered (ABS, MAEB, collision warning, curve warning, and curve assist) was evaluated against this expanded crash configuration taxonomy. That is, whether or not each safety system would

influence the crash configuration was assessed using the schematic vehicle movement information as described in the crash data.

Prior to the process of determining the relevance of each crash and vehicle configuration, the functionality, the purpose, and the applicability of the five safety systems were described, these being referred to as the ‘reference system’ (full details are provided in Table A1 in the Appendix).

Anti-lock brake (ABS) prevents wheel lock under abrupt or intense braking, and/or in conditions of low adherence between tire and road surface. Motorcycle autonomous emergency braking (MAEB) scans the frontal surroundings of the host motorcycle and anticipates possible collisions with other vehicles or obstacles. As soon as the system identifies an inevitable collision event, a mild, autonomous deceleration of the host vehicle is deployed. At that point, if the rider has already started braking, the system deploys enhanced braking, assisting the rider in achieving the highest deceleration. Collision warning scans the frontal surroundings of the vehicle, issuing a warning to the rider when computed risk for collision exceeds a given threshold. Curve warning estimates the real-time state of the host PTW to compute the control actions required to safely maintain the vehicle on the road and in the correct lane. As soon as the gap between the computed manoeuvre and the actual manoeuvre performed by the rider exceeds given thresholds, warnings are issued to the rider. Curve assistance monitors the host vehicle dynamics and intervenes with a series of adjustments on the engine torque/ brakes when a potential loss of control is detected, thus contributing in keeping the vehicle under control along the rider’s intended direction.

Following this description, for each safety system a four-category scheme for estimated relevance was developed ranging from 1 (system would not have applied to crash scenario) to 4 (system would definitely apply) (Table 1). For each category, specific and detailed rules were developed based on current understanding of device functionality. No consideration was given to the *likely crash avoidance or crash mitigation effectiveness of each safety system*, but rather the question was one of whether the system would be of relevance to the crash scenario; this has alternatively been described as ‘applicable crashes / countermeasures’ (Knipling 1993), ‘sensitive vs. non-sensitive crashes’ (Rizzi *et al.* 2015) or in the ‘field of influence’ of the countermeasure in question (Fitzharris 2013).

In order to standardise the coding for each safety system, two researchers (R1 and R2) independently categorised each of the 152 DCA crash scenarios into one of the four ‘relevance’ categories in accordance with the specific classification rules. Ratings could be in agreement (difference score of 0 translates to the same rating given); 1 apart (difference in rating of 1 category); 2 apart; and 3 apart. A third researcher (R3) independently assessed classification agreement. The three researchers were academics with ten years or more of experience in the development (R1 and R2, authors GS and

MP) and assessment (R3, author MF) of vehicle safety systems. The final classifications are presented in Table A3 in the Appendix with the details of the analysis of the level of agreement of the categorisation.

Data Analysis

Having assigned the relevance classifications to the crash data, the number of motorcycle crashes by relevance category was examined. Each safety system was considered independently and in combination. A distinction was made between crash severity and further analysis was conducted to understand the number of crashes and road users involved by DCAs with high relevance (3 and 4 level category).

In addition to presenting the number of motorcycle involved crashes and persons involved by 'relevance' category, the societal cost of these crashes is presented using established cost of injury values determined by the Australian Government. The dollar values for 'fatal', 'serious injuries' and 'minor injuries' were assumed to be \$AU 4,938,964, \$AU 804,618.00 & \$AU 29,709 per incident case respectively. Details of these estimates are provided in the Appendix.

Approvals

Use of the Crash data was approved by the Monash University Human Research Ethics Committee and VicRoads.

RESULTS

In the period 2000 - 2011 inclusive, there were 472,837 persons involved in 183,871 crashes. Of these crashes, 23,517 (or 12.8%) involved at least a motorcycle. Motorcycle riders represented 5.4% of crash-involved road users (n = 23,955) while pillion passengers represented additional 0.27% of persons involved (n = 1292). Table 2 presents the number of motorcycle riders and pillion passengers by injury severity. Data presented in Table 2 also highlights the injurious nature of motorcycle crashes, with motorcyclists representing 13.3% of road users killed and seriously injured, noting the registration data for 2011 showing the 3.4% of registered vehicles were motorcycles (including motor scooters and mopeds). For the purposes of the system relevance analysis, we excluded pillions as the motorcycle itself is the unit of measure; in practical terms, this avoids double counting.

Analysis of the 'relevance' of crashes for each safety system

The primary aim of this paper was to assess the proportion of crashes 'relevant' to each of the safety systems. Table 3 presents the number and proportion of motorcycle-involvements by 'relevance-category'. ABS was seen to be 'relevant' at category 2, 3, or 4, for 93.1% of crashes, MAEB was relevant for 47.9% of crashes, collision warning for 58.4% of crashes, curve warning for 20.9% of crashes, and curve assist for 56.5% of crashes. The safety system with

the highest percent of crashes classified in category 4 was ABS (40.6%), followed by collision warning (23.1%), curve assist (16.1%), curve warning (15.8%), and MAEB (5.7%). Category 3 of relevance is particularly important for MAEB and collision warning, accounting for respectively 17.3% and 20.5% of the crashes, whereas it accounts only for 2.3% of the crashes for ABS and 3.2% for curve assist.

Coverage of crashes by safety systems alone and in combination

Table 4 presents the number of ‘system relevant’ crashes that would be covered by one or a combination of multiple systems. Notably, for 43% of motorcycles involved in crashes, none of the five safety systems were classified as being relevant where the DCA-vehicle movement was classified as category 4. Inclusion of category 3 (i.e., systems with forthcoming, extended functionality) captured only 4% more motorcycle crashes.

Using the category 4 ratings, ABS alone was relevant for 17.6% (i.e., none of the other systems were relevant for this set), while coverage was provided by the combination of ABS and collision warning (17.4%) and the triple combination of ABS plus collision warning plus curve assist (5.7%).

When excluding ABS the combination of curve warning and curve assist together covered additional 15.8% of crashes.

Economic cost of motorcyclist riders injured

The aggregate cost over the 12-year period 2000 – 2011 of injured motorcyclists was \$AU 11.07 billion (\$AU2012) (US\$7.70 billion; €6.67 billion), equating to an average yearly cost of \$AU 949.378 million (US\$663 million; €590 million). Those killed (2.3%) represented 23.6% of the total costs, those seriously injured (43.3%) represented 73.2% of costs and motorcyclists sustaining minor injuries (with or without treatment, 50.9%) accounted for only 3.2% of costs. Only 3.5% of riders (n = 835) were uninjured.

Table 5 presents number and associated financial cost of injury by severity and for each ‘system relevant’ scenario. This provides a further basis of assessing coverage afforded by each safety system. It is apparent that the selected safety systems provide greater coverage the more severe the crash outcome. Specially, the safety systems, alone or in combination, provide a higher degree of coverage for crashes where a motorcyclist was killed (73.9%) than where a motorcyclist was seriously injured (61.2%) and where the injury outcome was minor (52.7%). This is an important finding as the safety systems address crashes at the more severe end of the spectrum.

Table A2 (in the Appendix) presents the results of the technological coverage, again in terms of numbers and cost, when combining category 3 and category 4 ratings. The inclusion of category 3 in the criterion of relevance slightly increased the technological coverage, respectively of 5.7%, 3.9% and 3.9% for fatality, serious injury, and minor injury crashes. However, the percentage of cases in which ABS was the sole relevant safety system reduced from more than 20% to less than 1%, whereas the percentage of cases in which a combination of safety systems including MAEB was relevant passes from less than 6% to more than 23% of the motorcycle crashes.

DISCUSSION

The paper is designed to reflect the functionality and hence applicability of five safety systems to the known crash problem and to enumerate *potential* cost savings associated with each. With the exception of ABS, none of the crash-involved motorcycles had the safety systems fitted, representing an ideal ‘base case’ of potential crash savings. Based on ABS fitment rates (*Fildes et al.* 2015b, Department of Infrastructure and Regional Development 2017) a small proportion (between 0.9% and 1.7%) of the crash-involved motorcycles would *likely* be fitted with ABS and according to our taxonomy, ABS would likely apply to less than half of these crashes. The considered data therefore represent an important base case upon which system regulatory impact statements and system ‘use-cases’ can be based.

In the taxonomy created in this paper, an a-priori reference definition of each safety system with respect to functionality, purpose and applicability was established, after which reference criteria were established based on vehicle movements and crash configuration, braking, location and obstacle struck. The inclusion of vehicle movement codes within a crash configuration provides greater precision in the analysis of mass data and the relevance of safety systems to specific crashes (see Figure A1 in the Appendix where vehicle number can be seen in each graphical representation of crashes). This provides valuable heuristics that can be applied to the five key safety systems considered as they evolve and are installed onto PTW. It must be noticed that the taxonomy established in this paper for ABS is different from other recent research. For reasons of space, a detailed comparison of the differences in the taxonomies is provided in the Appendix.

When considering the maximum possible coverage of crashes with the minimum number of safety systems, ABS alone had the highest relevance, with the system relevant to 41% of all crashes and 43% of serious and fatal crashes. Notably, Rizzi et al. had obtained similar results for Sweden, using a combination of in-depth crash analysis and induced exposure methods: ABS relevance was estimated to be 38% on all crashes and 48% on severe and fatal crashes (*Rizzi et al.* 2009). In our study, crashes in which ABS was relevant were estimated to account for 46.5% (\$AU 5.12 billion) of the total motorcycle-crash related costs (\$AU 11 billion).

Considering two safety systems at a time, the highest relevance was obtained with a combination of ABS and curve assist, which were relevant to different sets of DCA codes with no overlapping. Together, these two safety systems would have applied to 57% of crashes, with these crashes costing the community \$AU 7.25 billion.

Crash cases in which two or more safety systems apply can potentially benefit from the combined effects of these technologies. For example, in almost half of ABS-relevant crashes the PTWs involved could have exploited the safety potential of collision warning and MAEB. In almost all the cases where collision warning was considered that it would ‘definitely apply’ ABS was also deemed relevant. Where a rider may not have applied the brakes through lack of recognition of the impending collision, a collision warning system may have triggered their braking intervention, thus amplifying the effectiveness of ABS.

For one-quarter of the PTWs involved in crashes where both ABS and collision warning were relevant, MAEB was also a relevant safety system. MAEB could have provided additional support to the riders in the cases where they did not intervene, for whom ABS alone would not have had any effect. MAEB could also have supported riders that may not have responded adequately to the intervention of the collision warning, for whom not even a combination of ABS and collision warning may have been sufficient. ABS, collision warning, and MAEB can be combined to intervene in a sequence: first warning the rider; then assisting the rider during emergency braking (via ABS), and deploying an automatic intervention (via MAEB) when the warning does not produce an appropriate reaction in the rider. To gain optimal benefit, these systems ought to be implemented concurrently, given the likely lower cost of developing and fitting one system in combination with – and that relies on, the technology of the principal system.

One common requirement for safety systems that may prevent crashes, such as collision warning and MAEB, is a reliable obstacle detection system. Radar is about to be implemented in series motorcycles for the purposes of adaptive cruise control, but these automotive sensors may not be suitable for crash prevention on PTWs (Gil *et al.* 2017b). Attempts were made to adapt laser scanners for PTW use (Rössler *et al.* 2009). More recently, the advances in camera technologies and machine vision were exploited to develop a low-cost stereo-vision system for PTWs. The system underwent early testing in real traffic situations showing promising results (Gil *et al.* 2018).

When considering the relevance with both category 3 and 4 rating, the cases in which ABS alone was relevant drastically reduced, and the cases where MAEB was relevant in combination with ABS and collision warning increased by including intersection crash scenarios and turning PTW scenarios. In the perspective of the integrated approach, further development of the safety technologies to address the crossing scenario and the turning PTW is recommended.

Observing the crash configuration in which ABS was less likely to intervene, and also collision warning and MAEB were unlikely to apply, we found that 16% of PTW crashes (costing \$AU 2.11 billion to society in the considered

period) could have been positively influenced by curve warning and curve assist. This estimation based on system specification is similar to the figure provided by Biral *et al.* (2010). The authors stated that motorcycle accidents in a curve are in the range 15% - 17%, and typically caused by motorcyclists – thus supporting the need for rider assistance systems specific for curve scenarios.

In 2013 one type of curve assist, known with the name of cornering ABS, was introduced in series PTWs, starting from high-end motorcycles and then spreading to an increasingly larger number of models. This application of curve assist differs from the approach of the stability control system proposed by de Filippi *et al.* in the fact that cornering ABS can have a positive influence only if the rider is applying enough braking force, in analogy with standard ABS. A study conducted in Austria with mixed experimental and statistical methods, estimated that cornering ABS may positively influence 9% of PTW injury crashes (Sevarin *et al.* 2018). This is not far from the 16% applicability estimated in the present study for a more generic curve assist.

For almost all the PTW riders that may have benefitted of a curve assist, also curve warning may have represented a relevant system. Curve warning and curve assist can be designed to deploy in sequence in order to maximise their effects in preventing or mitigating the crash.

Monetary values provided in this paper represent the total scope of potential savings due to the safety systems. Actual saving is dependent upon the effectiveness of the safety system. In the best knowledge of the authors, figures on real-world effectiveness of the five presented safety systems are currently not available in the literature, except for ABS. For the latter, Rizzi *et al* (2015) in their multi-national study indicated an ABS effectiveness in the range 27% - 41%. However, even assuming lower effectiveness for the safety systems of 10%, as estimated in other European studies (European Road Safety Observatory 2018), and notwithstanding differences in crashes considered to be ‘sensitive’ and ‘non-sensitive’ (see above), the savings produced by their implementation would likely be significant. As an example, assuming a cost saving effectiveness of collision warning of a constant 10% on any type of sensitive cases, with 10% of the fleet equipped with the system, and the effectiveness not varying depending on the crash severity, costs savings in Victoria due to collision warning in the 12-year period 2000-2011 would be estimated in \$ 28 million.

As the study did not examine the likely effectiveness of the individual systems in preventing or mitigating crash events, this ought to be the focus of future studies. Whilst there is strong evidence as to the effectiveness of ABS, the estimation of the effectiveness of the other systems that are the subject of this applicability assessment will rely on a number of assumptions, given the fact that not all of them are currently available in the market. Factors such as rider experience, type of riding, road surface, and behavioural factors such as alcohol and drug use will all likely influence the effectiveness of these vehicle-control and warning systems, and ought to be considered, where possible.

It is worth noting that 43% of the crashes leading to injuries for the PTW users – including 142 fatality crashes and 4026 serious injury crashes, with an associated cost of \$AU 4.11 billion (31.7%) – were unlikely to be avoided or mitigated by any of the safety systems considered in this paper. These were typically situations involving other vehicles hitting a PTW that was either stationary or unable to execute any counteractions. This outcome leaves room to further analysis in order to identify additional safety systems or combination of systems to address the remaining crash scenarios.

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REFERENCES

- Australian Bureau of Statistics, 2014. Australian demographic statistics. Australian Government, Canberra, Australia.
- Australian Government, 2010. Best practice regulation handbook. Office of Best Practice Regulation, Department of Finance and Deregulation, Canberra, Australia.
- Biral, F., Da Lio, M., Lot, R., Sartori, R., 2010. An intelligent curve warning system for powered two wheel vehicles. *European Transport Research Review* 2 (3), 147-156.
- Biral, F., Lot, R., Rota, S., Fontana, M., Huth, V., 2012. Intersection support system for powered two-wheeled vehicles: Threat assessment based on a receding horizon approach. *IEEE Transactions on Intelligent Transportation Systems* 13 (2), 805-816.
- D'Elia, A., Newstead, S., Scully, J., 2013. Evaluation of vehicle side airbag effectiveness in Victoria, Australia. *Accident Analysis and Prevention* 54 (5), 67-72.
- De Filippi, P., Tanelli, M., Corno, M., Savaresi, S.M., Santucci, M.D., 2014. Electronic Stability Control for powered two-wheelers. *IEEE Transactions on Control Systems Technology* 22 (1), 265-272.
- Department of Infrastructure and Regional Development, 2017. Early assessment regulation impact statement: Advanced motorcycle braking systems for safer riding. Department of Infrastructure and Regional Development, Canberra, Australia.

- Department of Transport, 2012. Transport research and policy analysis bulletin. Department of Transport, State Government of Victoria, Melbourne, Australia.
- European Commission, 2011. Roadmap to a single European transport area – Towards a competitive and resource efficient transport system. Brussels, Belgium.
- European Road Safety Observatory, 2018. Advanced Driving Assistance Systems, report retrieved on 16th January 2019 at: https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/pdf/ersosynthesis2018-adas.pdf
- Fildes, B., Newstead, S., Rizzi, M., Fitzharris, M., Budd, L., 2015b, Evaluation of the effectiveness of anti-lock braking systems on motorcycle safety in Australia, MUARC Report n. 327, Monash University Accident Research Centre, Monash University, retrieved on 10/01/2019 at: <https://www.monash.edu/muarc/our-publications/2015>.
- Fitzharris, M., 2013. Electronic stability control and side impact crashes: 100% cure or a case of realigning safety priorities, paper number 13-0248. In: Proceedings of the 23rd International Technical Conference on the Enhanced Safety of Vehicles, Seoul, Korea.
- Gil, G., Savino, G., Piantini, S., Baldanzini, N., Happee, R., Pierini, M., 2017. Are automatic systems the future of motorcycle safety? A novel methodology to prioritize potential safety solutions based on their projected effectiveness. *Traffic Injury Prevention*, 18 (8), 877-885.
- Gil, G., Savino, G., Piantini, S., & Pierini, M. (2017b). Is stereo vision a suitable remote sensing approach for motorcycle safety? An analysis of LIDAR, RADAR, and machine vision technologies subjected to the dynamics of a tilting vehicle. *Proceedings of the 7th Transport Research Arena TRA*, Vienna, Austria.
- Gil, G., Savino, G., Piantini, S., & Pierini, M. (2018). Motorcycle that see: Multifocal stereo vision sensor for advanced safety systems in tilting vehicles. *Sensors (Switzerland)*, 18(1). <https://doi.org/10.3390/s18010295>
- Huth, V., Lot, R., Biral, F., & Rota, S., 2012. Intelligent intersection support for powered two-wheeled riders: A human factors perspective. *IET Intelligent Transport Systems*, 6(2), 107–114.
- Knipling, R.R., 1993. Ivhs technologies applied to collision avoidance: Perspectives on six target crash types and countermeasures. In: Annual Meeting of IVHS America. Intelligent Vehicle Highway Society of America, Washington, DC, USA.
- Lie, A., Tingvall, C., Krafft, M., Kullgren, A., 2004. The effectiveness of ESP (Electronic Stability Program) in reducing real life accidents. *Traffic Injury Prevention* 5 (1), 37-41.
- Matschl, G., 2014. Motorcycle stability control - MSC: The next step into safety solutions for motorcycles. IFZ International Motorcycle Conference. Cologne, Germany.
- Rizzi, M., Strandroth, J., Tingvall, C., 2009. The effectiveness of antilock brake systems on motorcycles in reducing real-life crashes and injuries. *Traffic Injury Prevention* 10 (5), 479-487.
- Rizzi, M., Strandroth, J., Kullgren, A., Tingvall, C., Fildes, B., 2015. Effectiveness of motorcycle antilock braking systems (abs) in reducing crashes, the first cross-national study. *Traffic Injury Prevention* 16 (2), 177-183.

- Rogers, N., 2008. Trends in motorcycles fleet worldwide. Presentation to joint oecd/itf transport research committee workshop on motorcycling safety.
- Rössler, B., & Kauvo, K. (2009). Laserscanner based ADAS for motorcycle safety. In *Advanced Microsystems for Automotive Applications 2009: Smart Systems for Safety, Sustainability, and Comfort* (pp. 245–253).
- Savino, G., Pierini, M., Baldanzini, N., 2012. Decision logic of an active braking system for powered two wheelers. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 226 (8), 1026-1036.
- Sevarin, A., Gruber, M., Tomasch, E., & Rathgeb, C. (2018). Safety Potential Assessment Of Cornering ABS Systems Based On Riding Tests. Paper presented at the IFZ International Motorcycle Conference Cologne, Germany.
- VicRoads, 2014a. Motorcycle licence and learner permit. State Government of Victoria, Melbourne, Australia.
- VicRoads, 2014b. Summary statistics of current ptw licence holders. VicRoads, Kew, Australia.

TABLES

Table 1. Criteria adopted in the rating process

	<i>Relevance Rating</i>			
	<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>
<i>Safety system</i>	<i>Would have definitely NOT applied to crashes belonging to this specific scenario</i>	<i>Would possibly have applied (controversial)</i>	<i>Would probably have applied (technical challenges still need to be solved)</i>	<i>Would have applied (typical configuration)</i>
ABS	Braking was not a relevant countermeasure in the given scenario	Opponent vehicle from behind; single vehicle & braking may have been crash causation	With opponent vehicle & braking may have been crash causation; braking was a relevant countermeasure & PTW on curve / turning	Braking was a relevant countermeasure & PTW on straight
MAEB	No obstacle / no vehicle; other vehicle hitting PTW from behind; stationary PTW	Narrow obstacle; PTW on curve / turning; head on collision; other vehicle hitting PTW; side swipe	PTW on straight hitting not narrow, moving obstacle	Rear end collision; not narrow object, fixed obstacle & PTW on straight
Collision warning	No obstacle / no vehicle	Obstacle in the scene, not clear how the warning could have applied (e.g. opponent from behind, stationary PTW)	Turning obstacle; PTW on curve / turning	Obstacle / vehicle in path & PTW on straight
Curve warning	No curve; PTW on straight	PTW running off at junction	PTW turning at junction	PTW on curve
Curve assistance	No curve / no turn & no stability issue	Loss of control in complex scenario; loss of control in a straight	Collision with obstacle & PTW on curve / turning	PTW on curve

Table 2. Number and percent of motorcycle riders and pillion passengers involved in road crashes, 2000-2011, by injury severity.

Injury severity	Motorcycle riders			Motorcycle pillion passengers		
	Number	Percent of motorcycle riders	Percent of total persons		Percent of motorcycle pillions	Percent of total persons
Killed	544	2.3%	13.3%	17	1.3%	0.4%
Serious injury	10,369	43.3%	13.3%	512	39.6%	0.7%
Other (minor) injury	12,207	50.9%	7.3%	623	48.2%	0.4%

Note. Killed: died at scene, en-route, or in-hospital. Serious injury: requiring treatment in hospital Minor/other/non-injury: no medical treatment in hospital, of any level; an ambulance may have attended.

Table 3. Number of crash cases ‘relevant’ to the selected safety systems (percent in brackets).

	Cat.1 (not relevant)	Cat.2 (possibly)	Cat.3 (probably)	Cat.4 (definitely)	Total
ABS	1,703 (7.1)	11,800 (49.3)	557 (2.3)	9,737 (40.6)	
MAEB	12,472 (52.1)	5,829 (24.3)	4,137 (17.3)	1,359 (5.7)	
Collision Warning	9,971 (41.6)	3,387 (14.1)	4,902 (20.5)	5,537 (23.1)	23,955 (100)
Curve Warning	18,957 (79.1)	1,060 (4.4)	NA	3,780 (15.8)	
Curve Assist	10,419 (43.5)	8,756 (36.6)	757 (3.2)	3,865 (16.1)	

Note: Involved motorcyclists ‘not in first crash event’ not classified and not shown (0.6%, n=158).

Note: Motorcyclists where DCA unknown not shown (0.03%, n=8).

Table 4. Number, percent and cumulative (C) of motorcycles involved in crashes with coverage from the selected safety systems, alone in and combination.

Safety system	Category 4 rating			Category 3 or 4 rating		
	Num.	%	C%	Num.	%	C%
<i>Single system</i>						
ABS alone (A)	4221	17.6	17.6	169	0.7	0.7
MAEB alone (B)	-	-	-	-	-	-
Collision warning alone (C)	21	0.1	17.6	276	1.2	1.9
Curve warning alone (D)	-	-	-	-	-	-
Curve assist alone (E)	85	0.4	18.0	197	0.8	2.7
<i>Two system combinations</i>						
ABS + Collision warning (AC)	4157	17.4	35.3	4022	16.8	19.5
Curve warning + Curve assist (DE)	3780	15.8	51.1	3780	15.8	35.4
<i>Three system combinations</i>						
ABS + MAEB + Collision warning (ABC)	1359	5.7	56.8	5496	22.9	58.4
ABS + Collision warning + Curve assist (ACE)	Nil	Nil	Nil	607	2.5	60.9
None apply	10,332	43.1	100	9370	39.1	100
Total	23,955	100		23,955	100	

Note. Combinations of safety systems with no additional coverage are not shown.

Table 5. Number and percent of motorcycles involved in injury crashes with coverage from the selected safety systems based on a category 4 relevance rating, alone and in combination.

Safety system	Category 4 rating							
	Killed		Serious injury		Other (minor) injury		Total	
	Num.	Cost	Num.	Cost	Num.	Cost	Num.	Cost
	(%)	(\$, million) (%)	(%)	(\$, million) (%)	(%)	(\$, million) (%)	(%)	(\$, million) (%)
None apply	142 (26.1)	701.33 (26.1)	4026 (38.8)	323.94 (38.8)	5776 (47.3)	171.60 (47.3)	9944 (43.0)	4112.3 (36.1)
Single system								
ABS alone (A)	132 (24.3)	651.94 (24.3)	1985 (19.1)	159.72 (19.1)	2027 (16.6)	60.22 (16.6)	4144 (17.9)	2309.3 (20.3)
Collision warning alone (C)	2 (0.4)	9.88 (0.4)	10 (0.1)	0.80 (0.1)	9 (0.1)	0.27 (0.1)	21 (0.1)	18.2 (0.2)
Curve assist alone (E)	Nil	Nil	30 (0.3)	2.41 (0.3)	54 (0.4)	1.60 (0.4)	84 (0.4)	25.7 (0.2)
Two system combinations								
ABS + Collision warning (AC)	124 (22.8)	612.43 (22.8)	1826 (17.6)	146.92 (17.6)	1932 (15.8)	57.40 (15.8)	3882 (16.8)	2139.1 (18.8)
Curve warning + curve assist (DE)	117 (21.5)	577.86 (21.5)	1844 (17.8)	148.37 (17.8)	1752 (14.4)	52.05 (14.4)	3713 (16.1)	2113.6 (18.6)
Three system combinations								
ABS + MAEB + collision warning (ABC)	27 (5.0)	133.35 (5)	648 (6.2)	52.14 (6.2)	657 (5.4)	19.52 (5.4)	1332 (5.8)	674.3 (5.9)
Total	544 (100)	2,686.80 (100)	10,369 (100)	8,343.08 (100)	12,207 (100)	362.66 (100)	23,120 (100)	11,392.5 (100)

Note. Combinations of safety systems with no additional coverage are not shown.